

Decentralized energy-saving hydraulic concepts for mobile working machines

Professor Dr.-Ing. Johann Lodewyks

Competence Center Mechanische Systeme (CCMS), Hochschule Luzern, Technikumstr. 21,
CH-6048 Horw, Schweiz, E-mail: johann.lodewyks@hslu.ch

Dipl.-Ing. Pascal Zurbrügg

SUNCAR HK AG, Inspire c/o ETH Technoparkstr. 1, PFA H13, CH-8005 Zürich, Schweiz,
E-Mail: zurbruegg.pascal@bluewin.ch

Abstract

The high price of batteries in working machines with electric drives offer a potential for investment in energy-saving hydraulic systems. The decentralized power network opens up new approaches for hydraulic- and hybrid circuits. In addition, the regeneration of energy can be used at any point of the machine. For the example of an excavator arm drive with a double cylinder two compact hydraulic circuits are presented, which relieve a central hydraulic system.

KEYWORDS: e-drive excavator, hybrid hydraulic system, energy regeneration, three areas cylinder drive, accumulator system

1. Introduction

The undeniable and physically justified advantages of hydraulic drives are the unmatched power density, reliability and easy generation of linear movements. This contrasts with still the disadvantage of poor system efficiency. The causes of this are significant throttling losses that inevitably occur in a nearly incompressible medium at any kind of flow resistance. The advantage of a simple hydraulic drive structure is always connected to the disadvantage of large energy losses. Constant displacement pumps for the construction of a constant pressure grid and throttle controls for sensitive control and regulation of the drives are the main cause for the poor energy balance. This technology has enormous, systemic losses and is not capable of regenerating energy. The efficiency of hydraulic displacement units is, in many areas of the efficiency diagram as well as that of e-drives. There are therefore many years' efforts to develop hydraulic controls without throttle losses. Hydrostatic transmissions have proven themselves in practice for a long time in stationary applications with large

driving power. However, once the linear drives are to be used in the form of differential cylinders, it becomes difficult to connect the asymmetric flow rates of the consumer with the balanced volume flow of the pump /2/, /4/.

1.1. State of the art

Compensation options with the help of hydro transformers or storage systems have been found, but most of them are very expensive /6/, /8/. Other variants imply by shifting pressure and hence flow pulses which are noticeable in the driving behavior /3/, /5/. In stationary installations, the space advantage over a synchronous cylinder is large enough to employ such solutions only with a stroke of several meters.

The path of digital hydraulics is an alternative for smaller drives, because the switching dynamic even for bigger valves is increasing. Similar to a PWM signal in electrical engineering, an analog signal of individual pulses is composed of variable width /7/, /5/. Due to the complete opening of the valve most of the throttling losses are reduced. However, it is to be expected with considerable noise, which is at higher power range becoming a problem.

1.2. Mobile Hydraulic

An important field of hydraulics is mobile work machine industry, for example the in large numbers produced construction machines. The demands in the part of the drive technology are very high. The drives must not only be compact and powerful, but also very robust and insensitive to contamination and shock loads. In lifting equipment of all kinds high security requirements are valid. An accidental move of the load, for example an uncontrolled lowering of the lifting device must be prevented in any case. This is today ensured by load control valves or pipe rupture valves, but they cause additional throttle losses in the power flow.

The classic drive concept of a construction machine consists of a central energy source, the diesel engine and a central pressure supply unit, which may well consist of several pumps of different type. All hydraulic consumer units are supplied with energy by a constant-pressure system, and there are various ways of adapting the pressure level to the needs of the highest loaded consumer (LS, NFC) /5/. Recent studies have shown that it is energetically worthwhile to build a multi pressure network with graduated pressure levels /1/, /9/. These systems can also be combined with accumulator solutions.

2. Battery electrical excavator

A completely new situation arises when the diesel drive is replaced with a battery-powered drive. Then a high-voltage electric power is available in the entire operating device, which is even able to absorb large amounts of energy quickly in the case of regeneration. Now every consumer can optionally be operated electrically, hydraulically or as a hybrid. Each kind of drive solution can make sense based on the local requirements in the machine. Today, these are still special solutions that are not competitive in the breadth of applications. However, if energy prices increase again in the future and if emission regulations become more restrictive, then the market conditions will change in favor of these solutions. It is therefore today at the development of technically robust and practicable solutions, to be ready for the demands of the future.

One such example is a 16 t - excavator from the Japanese Takeuchi Company, which has been rebuilt at the ETH Zurich under the guidance of the company SUNCAR HK AG from a diesel drive to a battery-powered drive. The valuable construction space is used optimally, because the diesel tank, the exhaust gas treatment, the exhaust system and the diesel engine itself are not any longer necessary. Instead of these components, a compact frequency-controlled electric motor is used. The hydraulic system could be adopted without any change.

In the case of the excavator, the great weight of the batteries is not a disadvantage, because they simply replace the classic counterweight. The advantages of such a device are the "zero emissions" at the workplace, the low noise and a good and dynamic controllability of all working movements. The first experiences show, that the response of the electric motor is significantly faster and more sensitive. A pleasant, quiet, zero emission and vibration-free working is possible now. The high battery price today is the reason for substantially higher investment costs, that's why the market penetration is still limited. Cost advantages for the E-excavator expect first assessments after about seven or eight years, because of lower energy and maintenance costs.

The efficiency of the frequency controlled permanent magnet axial flow motor is located in many areas of the engine map by over 90% (**Figure 1**). Significant energy savings result therefore in comparison to the diesel engine which has an efficiency of about 35% in maximum. At the same time the rectangular form of the characteristic field fits much better to a hydraulic drive, because now the corner power can be exploited. In addition, both components are able to regenerate energy.

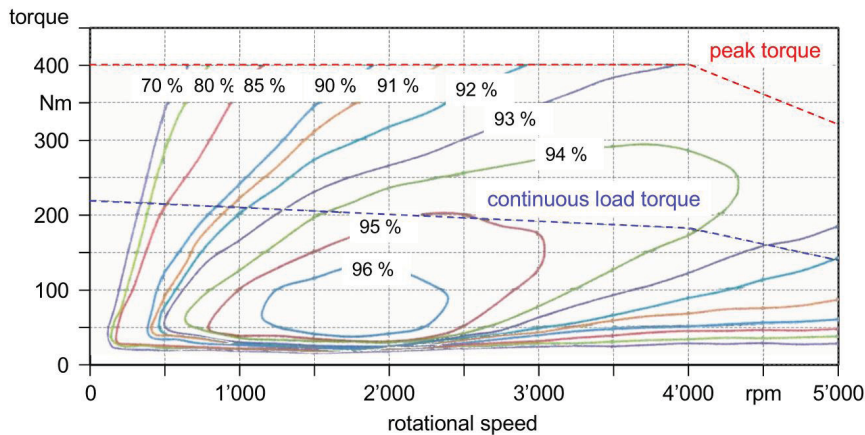


Figure 1: Characteristic curves of the axial flow motor

With this drive concept, a continuous operation time of six hours is possible. Even without optimizing the hydraulic system. For a comprehensive eco balance also the way of power generation is to be regarded. But as well the power generation cost of oil is rising (deep water drilling, oil sand, fracking) and so a simple answer to this question is not possible.

2.1. Energy management solutions

The energy management system can now be reconsidered and it begs the question: What role can the hydraulic system play in such a device? The high battery costs (>100'000 CHF) justify a higher investment budget for energy-saving drive solutions.

The following scenarios are conceivable:

1. E - actuators replace the hydraulic drive
2. Hydraulic Stand-Alone Drives are used
3. Hydrostatic Drives are used
4. Hydro Transformers for linear actuators are used
5. Digital Hydraulic Drives for auxiliary equipment
6. Secondary controlled motors at constant pressure network

The use of an electro-mechanical linear drive in the excavator is severely limited. Their low power density and the sensitivity to dirt and vibration are problematic. Stand-Alone Drives have the advantage that the power supply can be optimized for the individual exposure of the consumer. A pressure reduce from a constant-pressure network is not necessary and prevents losses. The individual pressure generation caused a greater expenditure of components and is therefore a disadvantage.

Hydrostatic Drives are useful for heavy-duty rotary actuators, such as the swivel drive of the superstructure, and correspond to the state of the art. However, linear drives require complex circuitry compensations and therefore often require too much construction space. The Hydraulic Transformer is a very smart way to adapt asymmetrical consumers at a constant pressure network. So far, however, there are no such components that have prevailed in the market.

The Digital Hydraulics is limited by the performance of switching valves. An increase in the volume flow is possible by parallel connection of several valves. In fact thereby the expenses for each drive increase significantly. The secondary control is an energetically interesting solution for rotary actuators at a constant pressure network. The separation of the motor part and pressure supply part, allows optimizing the pump drive regardless of the demands of the consumer's /1/. However, linear actuators cannot work without additional components at a constant pressure network.

2.2. Regeneration

An important contribution to the efficiency improvement is the consistent use of energy regeneration. Lifting devices offer potential energy and all braking processes kinetic energy that can be used. Therefore compact and powerful energy storage devices are required. A comparison of electrical, mechanical and hydraulic energy storage devices shows that the classical hydraulic accumulator has very good results and works with high efficiency (**Figure 2**).

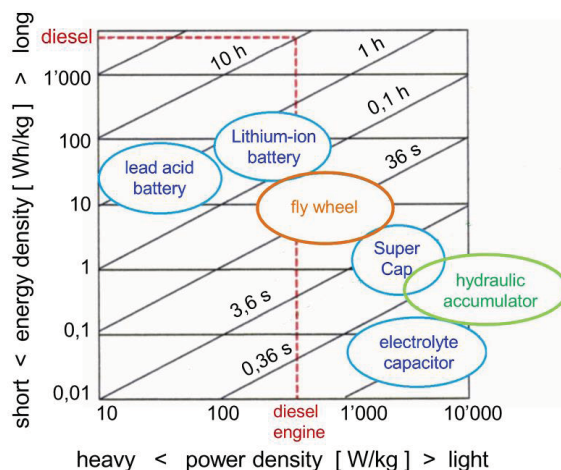


Figure 2: Comparison of energy storage devices

The braking energy of rotational movements of the superstructure, for example, can be regenerated with a hydrostatic transmission to the e-power grid. It can however be recovered only half of the power, even if all components (hydraulic motor-hydraulic pump -E-motor) have an individual efficiency of 90 %, because the energy flows thru the whole chain of components in both directions. Nevertheless, the change makes sense, since the central hydraulic system is relieved and also the efficiency is significantly better than a throttle control.

The movement cycle of heavy excavator arm is a source of potential energy that should be noted. Based on the information about the maximum load of the excavator an overview of the load pressures can be calculated in the workspace (**Figure 3 left side**). There are work points at which the maximum load pressure of 227bar is not achieved, because the risk of tipping consists. The efficiency of a hydraulic throttle control is proportional to the ratio of load pressure and the supply pressure of the system. In an optimum control of the supply pump arises in looking at work space of the excavator, an average efficiency of hydraulic control of 54% at full load. This also is the maximum value achievable. The mean, mechanical drive power of the boom cylinder is 30kW. The magnitude of renewable energy can be estimated by considering the load pressures in the boom cylinder with a movement of the empty bucket (Figure 3 right side). The mean efficiency of the throttle control is lowered in this case to 23%. If a lowering operation carried out with an empty bucket and maximum working speed, which happens very often, so this corresponds to an average power of 12.7kW.

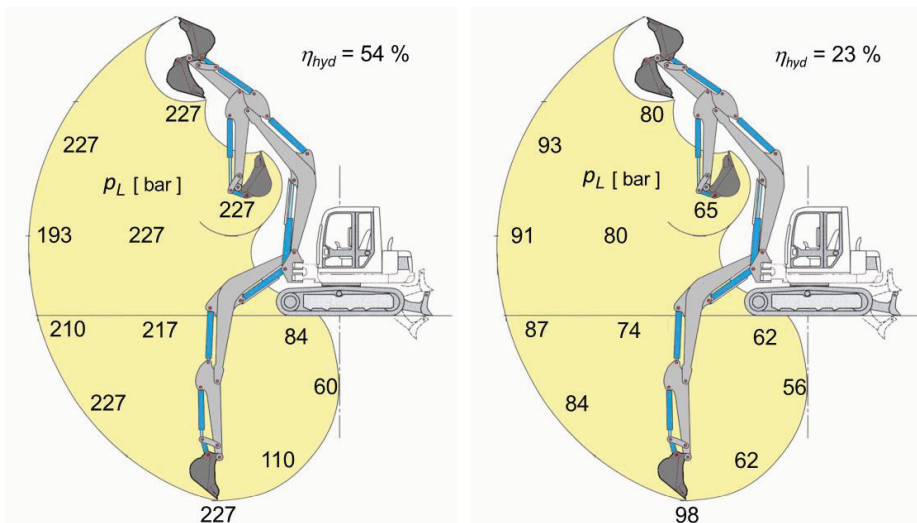


Figure 3: Maximum and Minimum load pressure in the boom cylinder

The benefits of the change from a diesel engine to an e-drive show the energy flow diagrams and the numerical example of the average power of the boom cylinder (**Figure 4**). The need for power is reduced from 200kW diesel fuel to 77kW of electrical power. At the same time it becomes clear that the throttling losses and the inability of regeneration are the greatest potential for further savings.

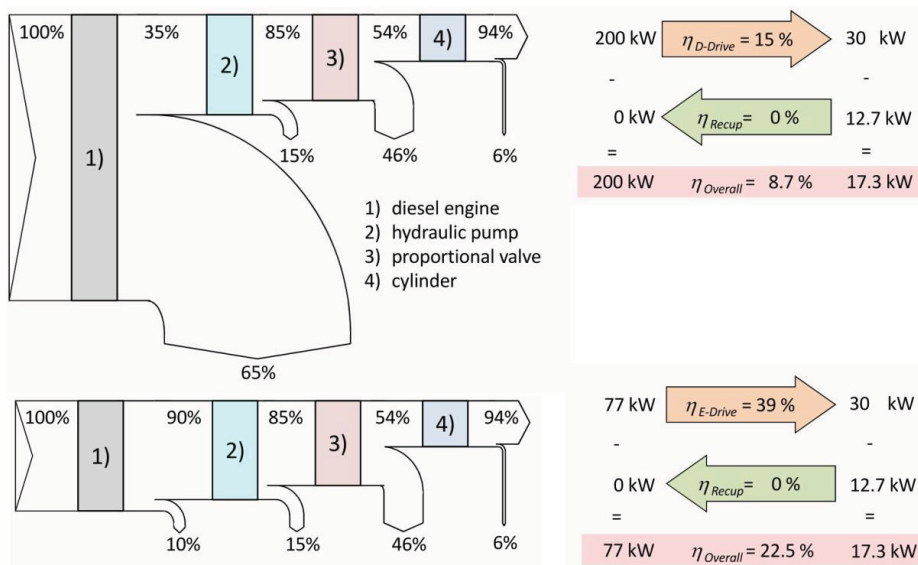


Figure 4: Efficiency comparison without a possibility of power regeneration

3. Three areas hybrid circuit

A three areas hybrid circuit for tandem linear actuators with an area ratio of 0.5 and with a large, static pressure load share (F_L) has been developed (**Figure 6**). This version combines many advantages of the already known solutions. The annular spaces of the tandem cylinders will be connected and thus act as an area with one pressure (p_B). The servo fixed displacement pump (HP) is connected to these annular chambers and a piston chamber and thus provides symmetrical area ratios. The third piston area with pressure (p_{A1}) can be connected to the pressure of the central hydraulic source (p_o), additionally (or exclusively) with an accumulator (SP) /10/. A feed pressure (p_{min}) supply compensates the pump leakage and prevents cavitation. The leak-free load holding at a standstill is achieved by switching valves. A separate pressure relief valve is not necessary if the drive torque of the servo constant pump (HP) is limited.

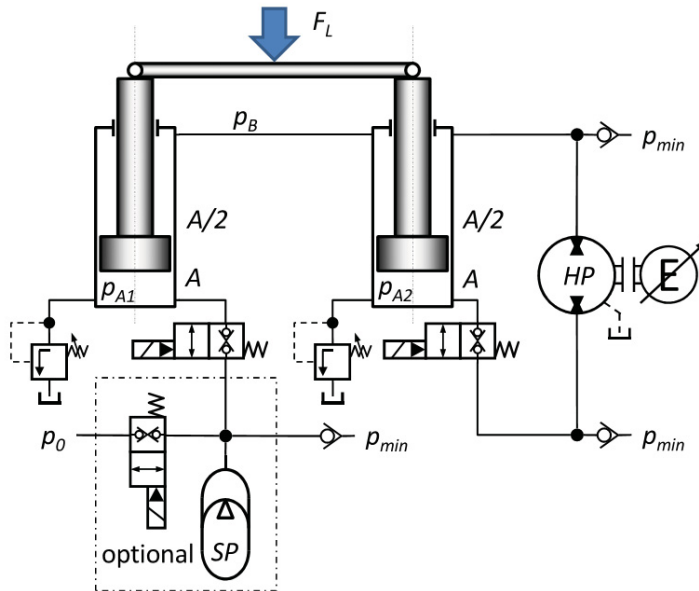


Figure 6: Three areas hybrid circuit for tandem cylinder drives

E-motor and fixed displacement pump can also be overloaded in the short term, so that the drive can also build train loads of approximately 20% of the pressure load and thus a four-quadrant operation is possible. The servo constant pump (HP) is speed controlled substantially. Load changes or variations in pressure (p_0) in the main circuit lead to positional errors in the field of oil elasticity, which is in the range of millimeters. The different pressure forces of the two cylinders are balanced by the massive mechanics of the boom arms again. An uncontrolled lowering of the load is reliably prevented by the redundancy of the drives, the blocking valves and the fact that the storage volume of accumulator is limited.

The energy flow diagrams (**Figure 7**) show the efficiency improvement in the drive part and in the regenerating part and the example of the power results in an efficiency increase to over 50%. This efficiency may optionally increase with the use of a 20 l - accumulator. Even if the storage volume takes over only 30% of the volume exchange, the effect with an increase in efficiency to 60% is significant.

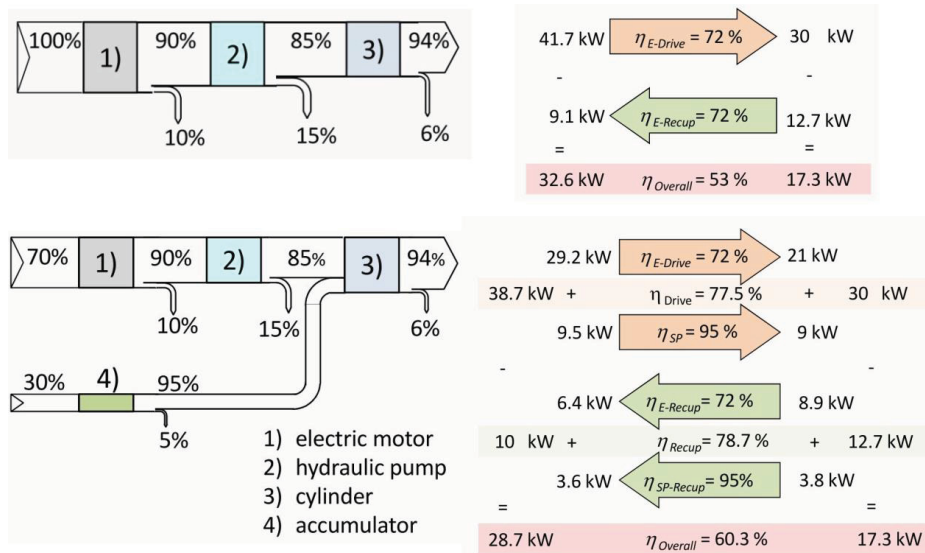


Figure 7: Efficiency comparison with the possibility of power regeneration

For this circuit configuration, the following advantages, which are particularly important for the lifting cylinder in an excavator, arise.

1. Compact cylinder with one piston rod
2. Flexible arrangement of the components
3. High safety level by redundant drives
4. All variants of hydrostatic drives are possible
5. Only one hydraulic motor unit without compensating elements
6. Only marketable hydraulic components are needed
7. Power regeneration in the electrical grid and/or with an accumulator
8. Least number of switching operations
9. Load distribution on hybrid drives
10. four-quadrant operation possibility

More advantages base on the connection to the Central hydraulics.

1. Flexible load distribution
2. Small, compact hydrostatic drive
3. Low installation space requirement near the cylinder
4. Easy and safe load holding at a standstill
5. Combination with multi pressure level systems is possible
6. Use of Load - Sensing possible
9. No throttling losses between central hydraulic and the cylinder control

Another variant can be used as a substitute for the arm cylinder (**Figure 8**), or even as a tandem unit, with balanced pressure conditions /11/, /12/, /13/, /14/. Disadvantage is the higher cost of such a special cylinder. In the case of E-excavator a hydrostatic drive with frequency controlled electric motor is particularly interesting. In return, high pressure hydraulic motors have the largest possible maximum speed, such as a bent axis motor with up to 10'000 rev/min. The high speed reduces the required displacement and thus the torque load on the electric motor. The entire unit is thereby very compact and can easily be integrated near the cylinder.

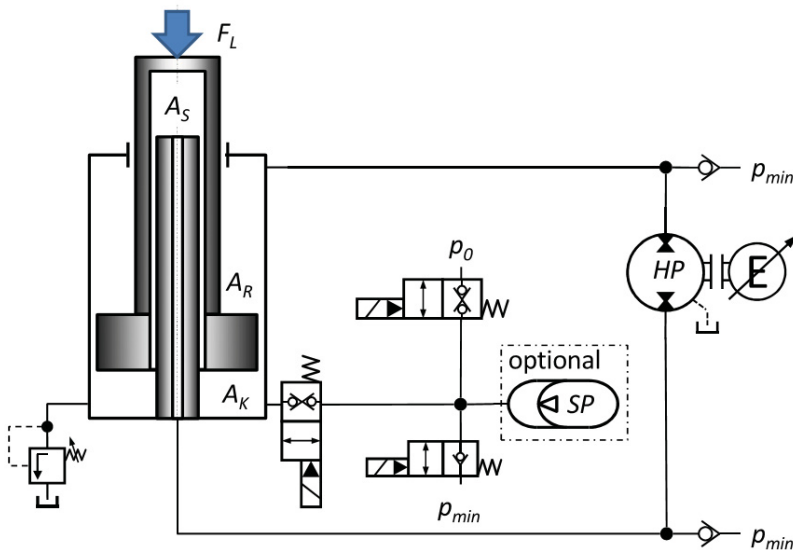


Figure 8: Three areas hybrid circuit for single or tandem cylinder

An initial cost-benefit analysis has shown that only an optimized boom cylinder can reduce the investment costs already at least 4.5% (5% with accumulator). The three area hybrid circuit is saving money from first day. In the further course of the project, such a drive is first constructed separately and examined on a test bench. In addition to the interaction of the hydraulic and electrical components an optimal drive and control concept has to be developed.

4. Summary

Disclosed is a three areas hybrid circuit, which has been specially optimized for lifting tasks in a work machine. It combines the advantages of a symmetrical hydrostatic drive with the advantages of a differential cylinder. The third piston area enables load sharing between direct drive and a central hydraulic system.

The direct drive may be a variable displacement pump, but also a fixed displacement pump with a frequency controlled electric motor. This combination makes sense, if the fixed displacement pump can run although the same high speed, the torque load of the electric motor decreases and the drive is smaller and more compact. The corner power can be exploited by two drive units and they are able to regenerate energy.

For the construction of the three areas hybrid circuit only marketable drive components are required and the drive can be flexibly integrated in different drive concepts. Both classical load sensing, as well as more recent approaches of a multi-level pressure network are conceivable. The redundancy of drives leads to a very high, systemic safety and reduces problems when starting up or when using numerous switching valves in the power section.

This compact drive concept is suitable for many lifting drives, also in the stationary area and the differential cylinder thus becomes a symmetrical consumer. The combination with a constant pressure network, which compensated the static loads, simplifies the control and allows optimizing the efficiency and the central drive.

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6. Nomenclature

η	efficiency	
p	pressure	bar
A	area	mm ²
F	force	N